Recommendations for Future IR High Spectral Resolution Observations

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Recent Developments Aiding Hyperspectral Observations

Hank Revercomb

Largely Extracted from this talk

University of Wisconsin - Madison
Space Science and Engineering Center (SSEC)

NOAA NASA EUMETSAT
Satellite Hyperspectral Sensor Workshop
Miami, FL, 29-31 March 2011

H-S Operational Technology Topics

A. General Perspective

B. Future LEO: Advanced CrIS for JPSS-Next

C. Advanced GEO Wx Sounder & Trace Gas Imaging FTS
(a la GIFTS/HES/GEO-CAPE, MTG/IRS, FY4)

D. IR Climate Benchmark
(a la CLARREO)

A. General Perspective (1)

Question 4:

- State of hyperspectral sensor technology for satellite applications (LEO, GEO orbits)?
  - **Mature, relatively low risk** (with some imaging FTS refinements needing careful demonstration)
- Is there a role for GHG measurements in GEO?
  - **A key role—** UW Geo Atmospheric Profiler (GAP) even identified as GEO component of original EOS concept
- Many questions about ***Minimal*** system for GEO
  - **With the right program model, GEO systems are affordable and the benefit-to-cost ratio is large** (***Minimal*** as defined for HES instrument or products would sacrifice performance by not really save much)

A. General Perspective (2)

Common Operational Requirements:

- Spectral Resolution Exceeding ~1 cm^{-1}
  - **Vertical resolution, Separation of contributions from different gases, Atmospheric spectral calibration**
- Broad-Band Spectral Coverage
  - **Needed to capture information content (overall S/N)**
- Spectral Stability/Knowledge ~1 ppm
  - **Even small shifts at moderate resolution create significant effective radiance errors**
- Spectral Consistency
  - **It should be possible to put spectra from different instruments on a common scale (requires Nyquist spectral sampling)--** avoids subtle differences from spectral property differences and allows product combining and common processing

A. General Perspective (3)

Comments on Organizational Structure:

- NASA and NOAA need to be close partners
  - **Technologies for new operational systems should be proven by NASA in response to NOAA needs.**
- NRC Decadal Survey should cover future Operational needs as thoroughly as new Science Missions
  - **Satisfying NOAA operational needs should be a NASA priority**
  - **Flaw in 2007 DS implementation, exacerbated by unfortunate timing of operational plan changes (e.g. GIFTS)**
- New procurement strategies for operational systems seem to be needed to constrain costs
  - **Need a process that incentivizes timely development and implementation of new systems**
  - **Example is commercial data sale approach where Mission investors want return as soon as possible and products need to be good to succeed (Dave Crain, Q 15 Talk 12)**

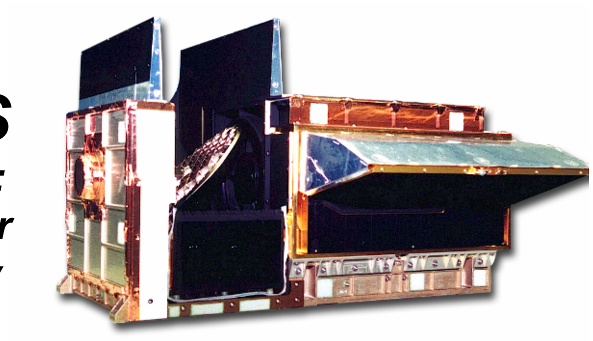
B. Future LEO: Advanced CrIS for JPSS-Next

Supporting new operational Goals beyond JPSS

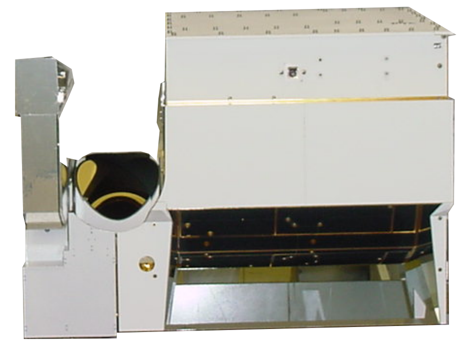
- Higher spatial resolution and near-contiguous foot prints
  - **Improved T & WV fields from better cloud avoidance**
  - **Better surface & near-surface T, WV by resolving unique surface properties**
- Multiple along-track angle viewing
  - **Measure water vapor fluxes from motion of distributions (Bill Smith's notion for GIFTS)**
  - **Improved height definition from stereo clouds and WV**
- Improved spectral coverage/resolution (CrIS)
  - **Additional trace gas information**
- On-orbit calibration verification a la CLARREO
  - **Enhanced climate change role**

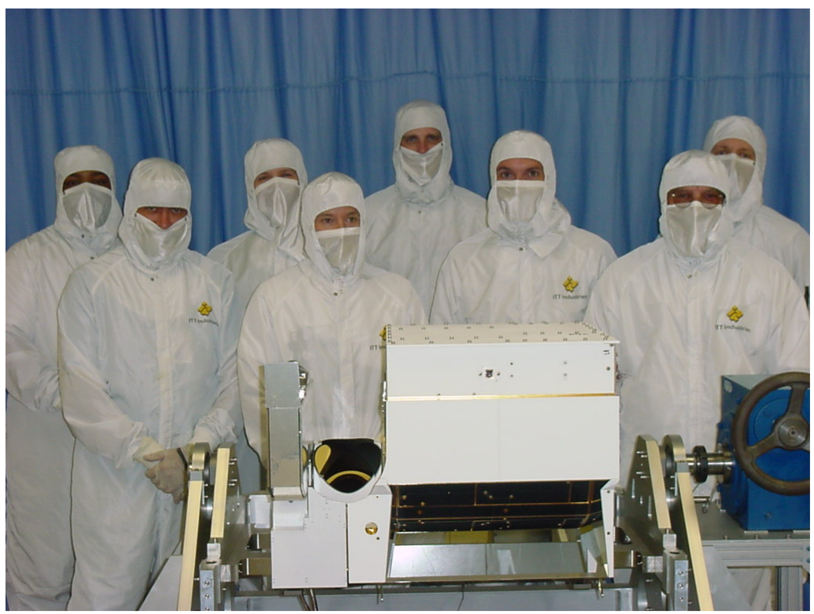
Current CrIS Instrument

HIRS
(20 ch):
30⁺ year
history



CrIS
(1307 ch):
NPP/JPSS

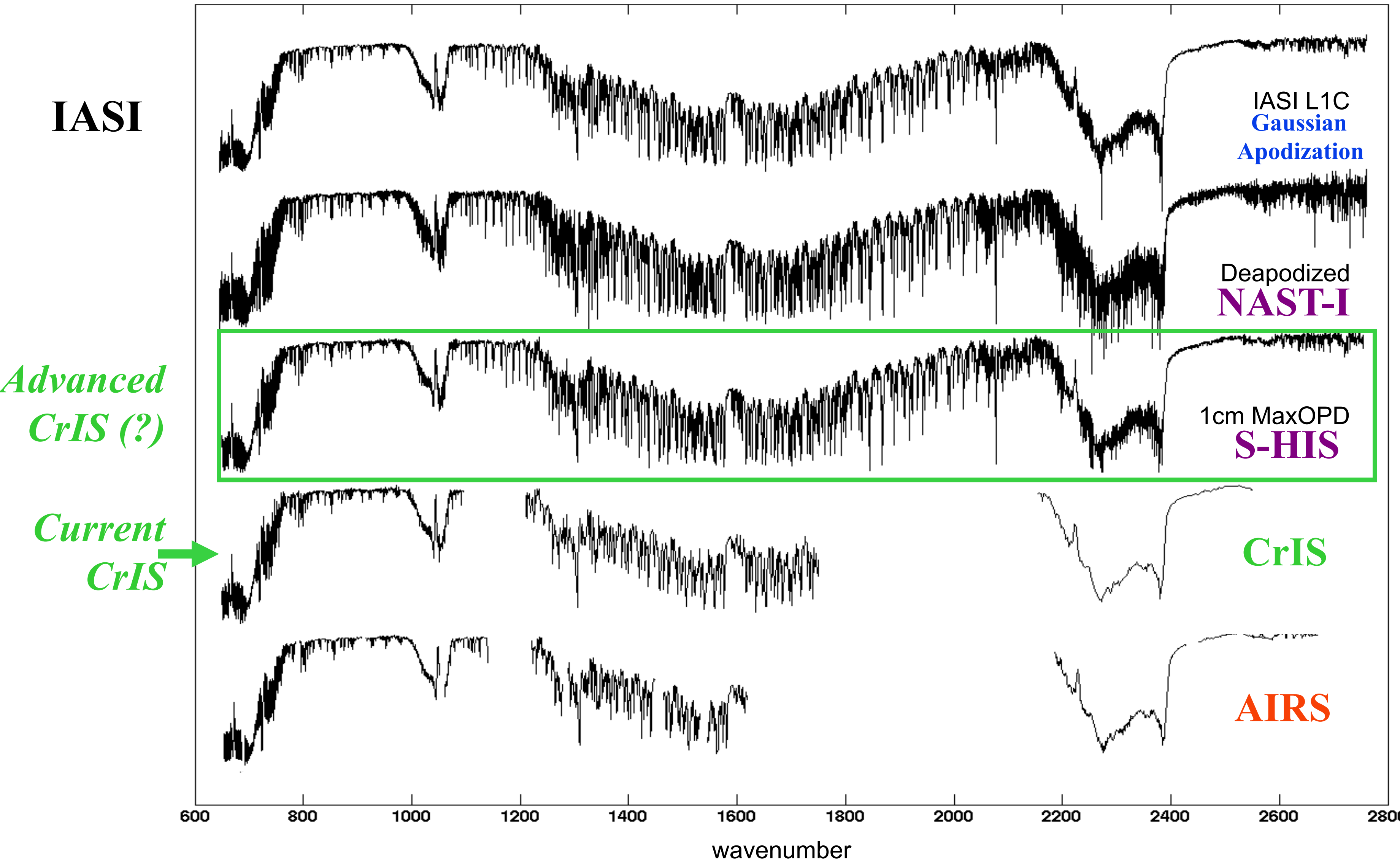




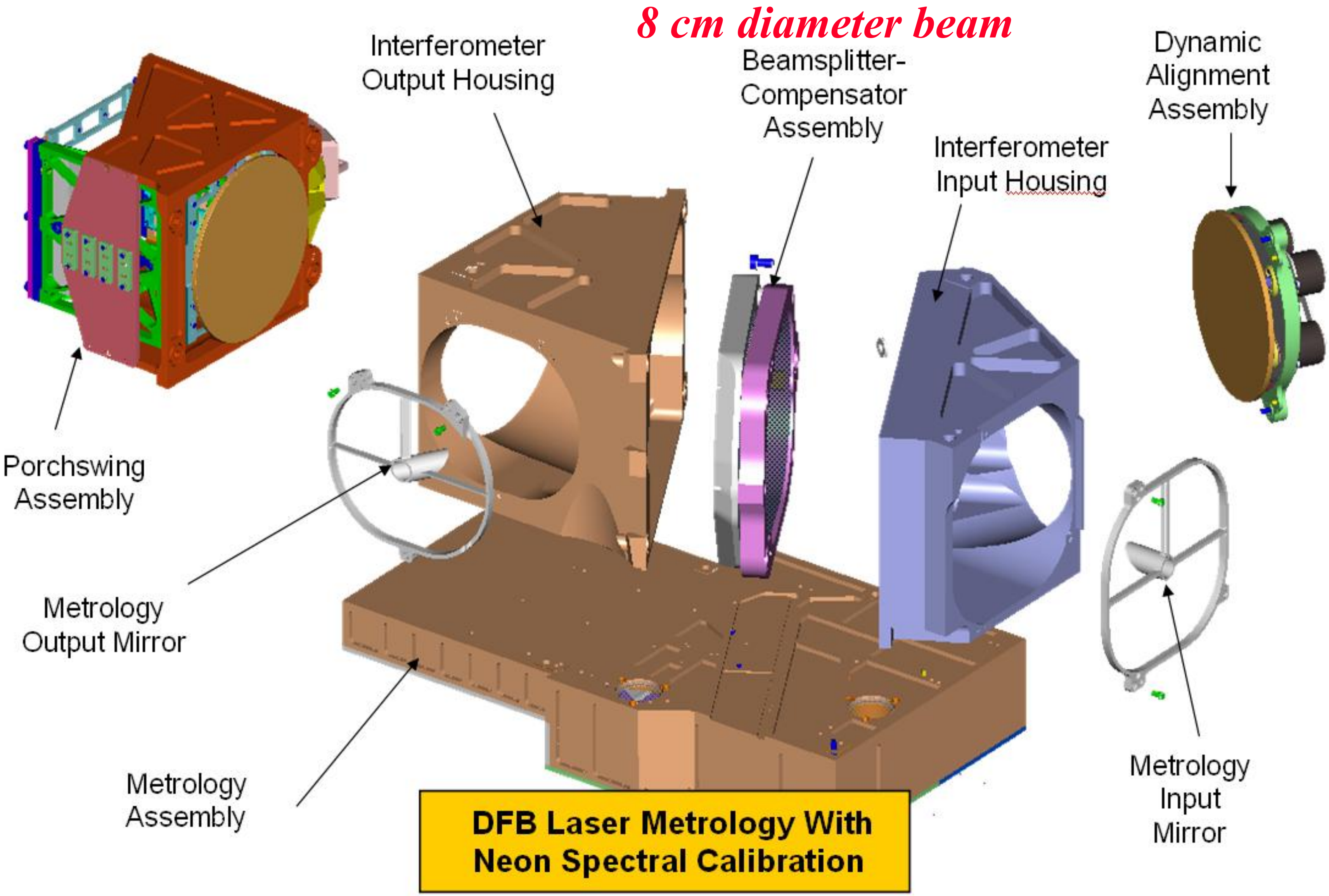
Volume: < 71 x 80 x 95 cm
Mass: < 152 kg
Power: < 124 W
Data Rate: <1.5 Mbps

from Williams, Glumb and Predina, ITT, August 2005 SPIE

Spectral Coverage of Advanced CrIS
Compared to IASI, CrIS, AIRS, S-HIS & NAST-I



Interferometer Design - Exploded View



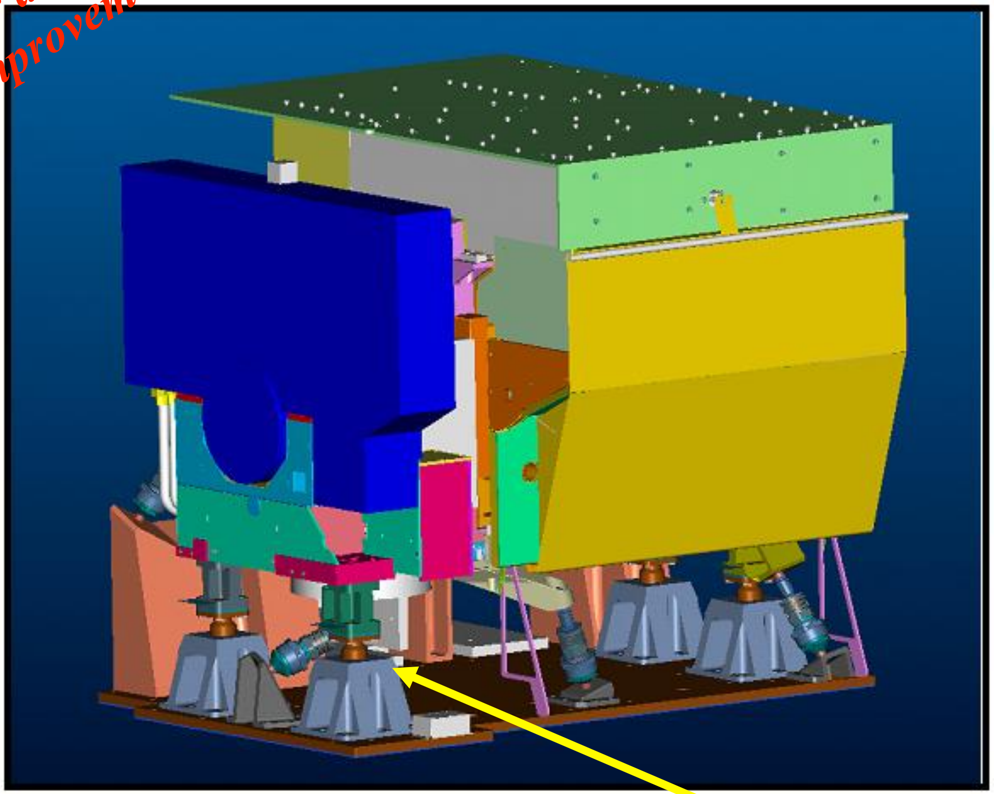
from Williams, Glumb and Predina, ITT, August 2005 SPIE

CrIS Utilizes Innovative Technologies to Achieve High Performance

CrIS Sensor Features

- Large 8 cm Clear Aperture
- Three Spectral Bands
  - LWIR: 650-1095 cm^{-1}
  - MWIR: 1210-1750 cm^{-1}
  - SWIR: 2155-2550 cm^{-1}
- 1305 Total Spectral Channels
- 3x3 FOVs at 14 km Diameter
- Photovoltaic Detectors in All 3 Bands
- 4-Stage Passive Detector Cooler
- Plane-Mirror Interferometer With DA
- Internal Laser Wavelength Calibration (Neon bulb)
- Deep-Cavity Internal Calibration Target
- Extended Radiator Supports 1394a
- Passive Vibration Isolation System Allows Robust Operation in 50 mG Environment
- Modular Construction

Advances: detector arrays & mechanical cooler allow spectral and spatial improvement



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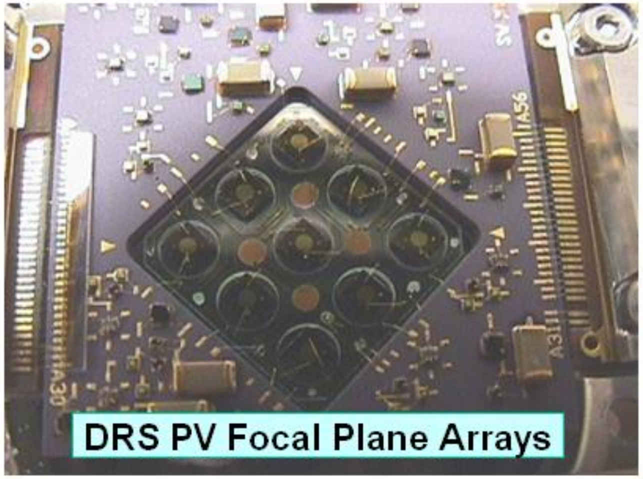
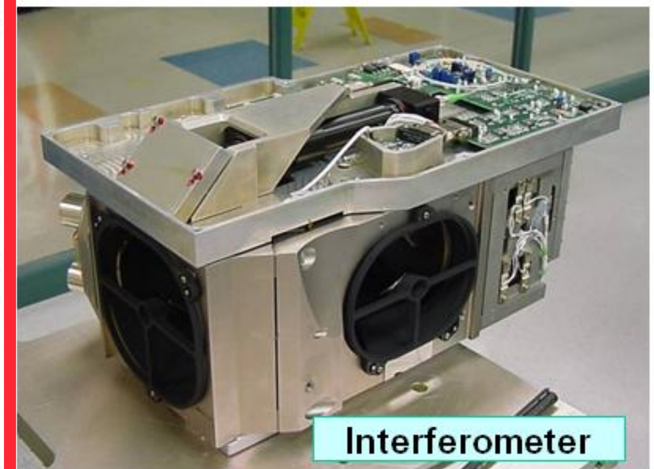
CrIS Subsystems (EDU3 shown)

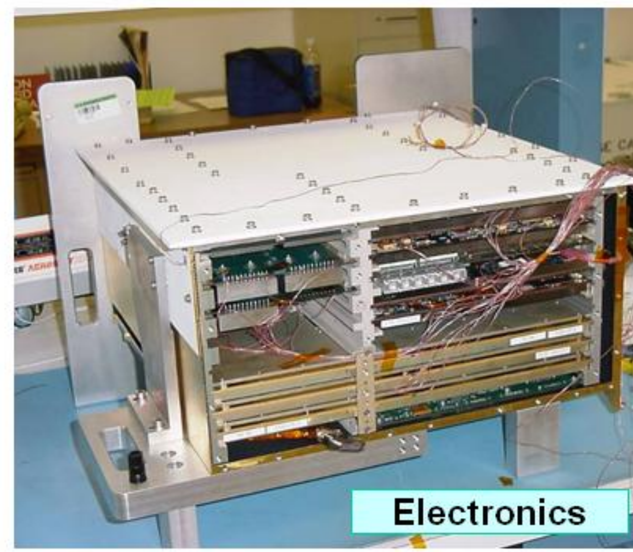

DRS PV Focal Plane Arrays


Interferometer


Telescope


4-Stage Passive Cooler


Optical Bench


Electronics

Modify to improve spatial resolution and spatial sampling

B. Future LEO Summary

The CrIS sensor provides a foundation that is well suited to the upgrades needed for NOAA's next generation Weather, GHG monitoring, & Climate Monitoring

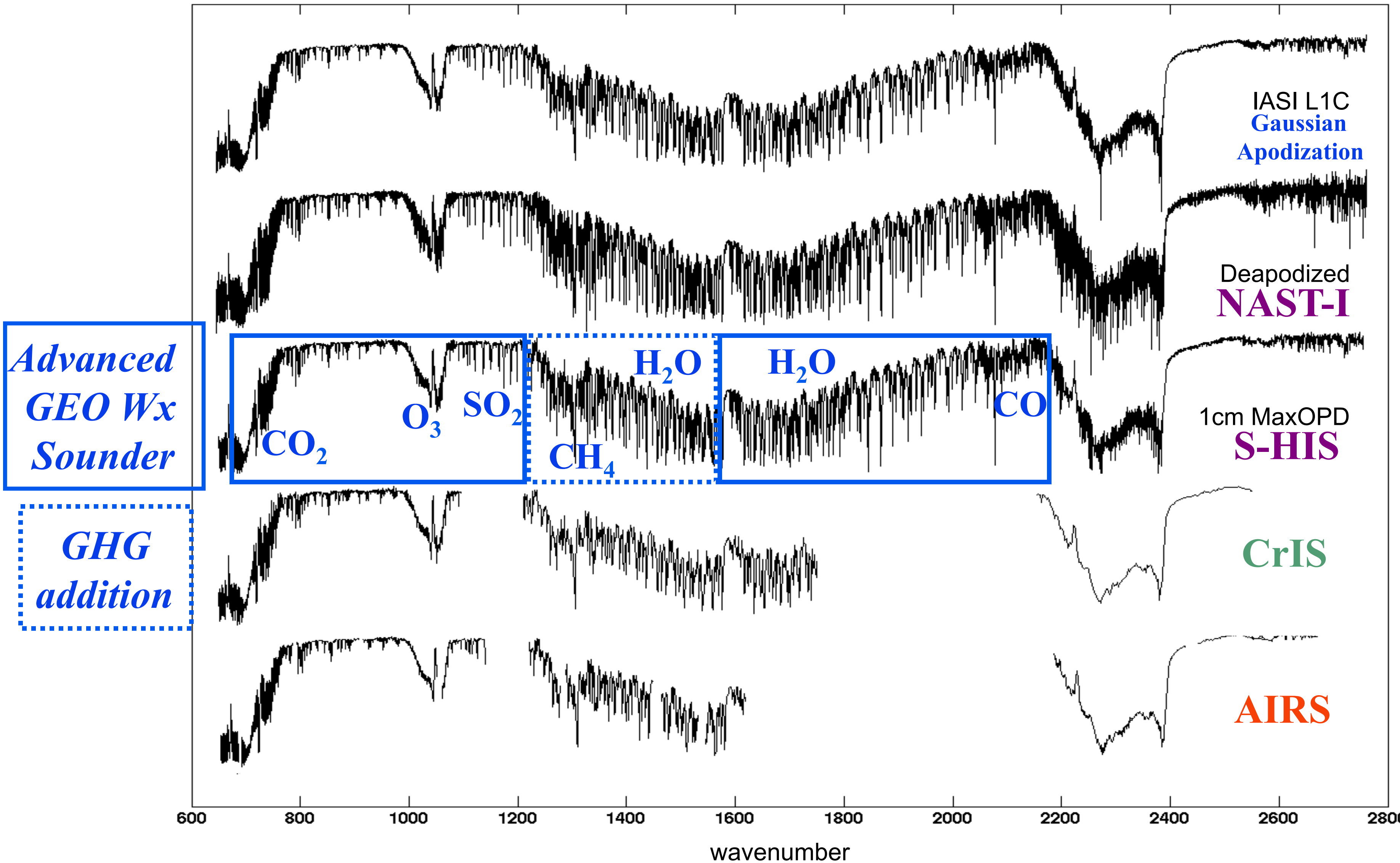
C. Advanced GEO Wx Sounder & Trace Gas Imaging FTS (a la GIFTS/HES/GEO-CAPE)

New Sensor needed to meet US Operational Goals

- Higher spatial, spectral, and temporal resolution
  - **Factor of 100 more space time-detail (x 2.5, y 2.5, z 3, t 5.5) in T & WV distributions**
  - **Hours advanced warning of serious severe storms**
- Spectral resolution for Green House Gas monitoring
  - **GHG transport information from time domain**
  - **GHG sensitivity increase from variable Tsurface**

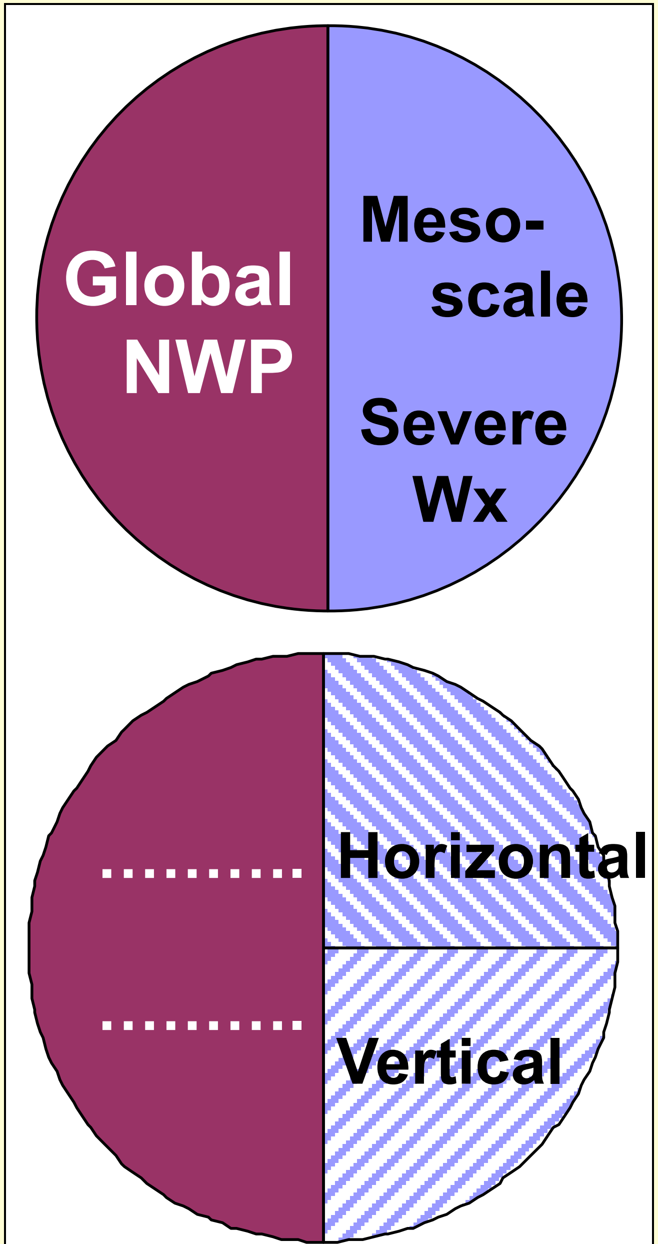
Spectral Coverage of GIFTS/IRS/HES

Compared to IASI, CrIS, AIRS, S-HIS & NAST-I

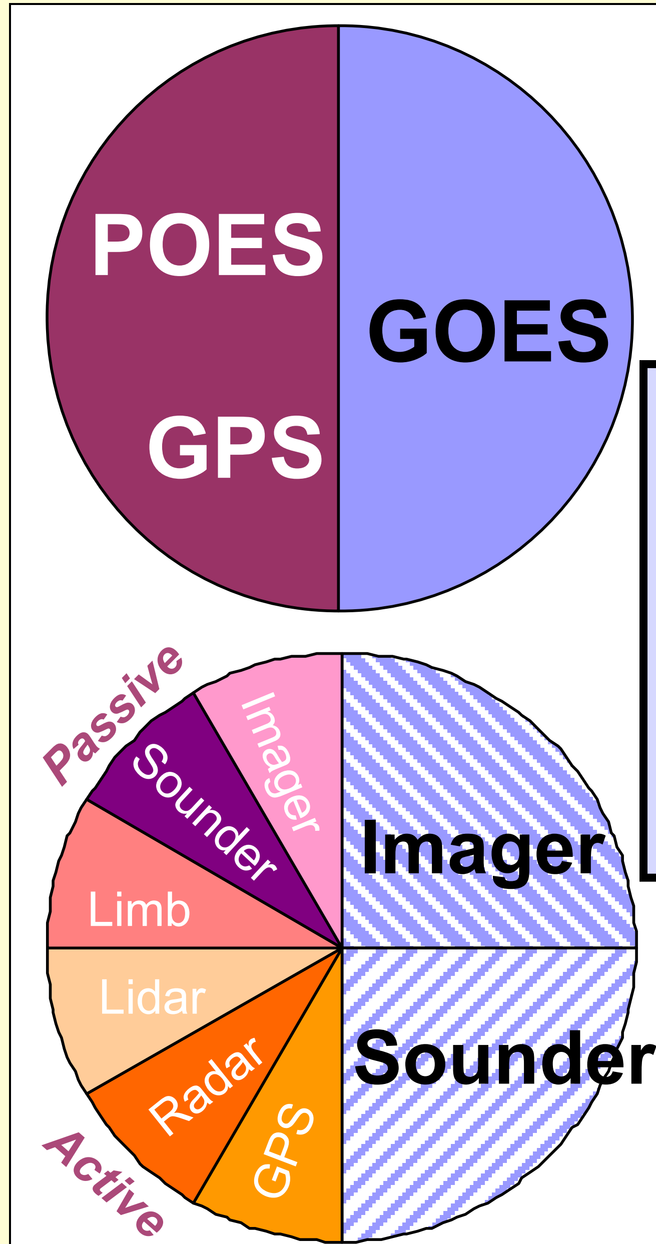


Operational Weather Satellites

ROLE



APPROACH



GOES Sounder

= ¼ Wx Sat. role

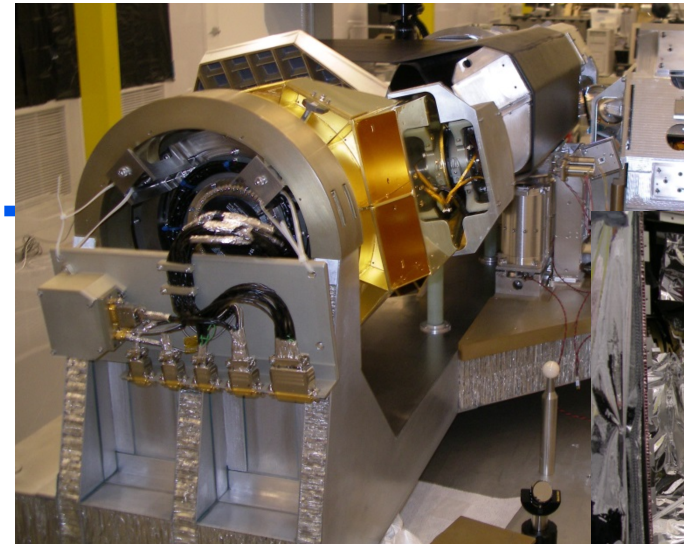
= ½ Severe Wx Sat. role

& can do trace gas too!

GEO IR Imaging Sounder capability is unique

- **Polar Sounders**:
  Inadequate temporal coverage
- **GPS**: Inadequate spatial resolution and temporal coverage
- **Current GEO Sounder**:
  Vertical resolution 2-3 times lower
- **ABI Imager**:
  Inadequate vertical resolution
- **GEO Microwave**:
  Vertical & horizontal resolution 2-3 times lower

Geosynchronous Imaging FTS



GIFTS EDU

- **GIFTS Proof of Concept was successfully demonstrated in 2006 with the Engineering Development Unit Thermal/Vacuum & Sky Viewing Tests**
(expected long-poles are working well: LW detector with good sensitivity and operability, Long-lived stable laser, mechanical cooler and cryogenic thermal design, imaging FTS radiometric integrity, plus many others)
- **Results Demonstrate that NOAA Requirements for a Successful GOES Imaging Spectrometer are achievable with a GIFTS Flight Model**
(spatial coverage and resolution, spectral coverage, spectral calibration and Instrument line shape knowledge, and spectral scale standardization)

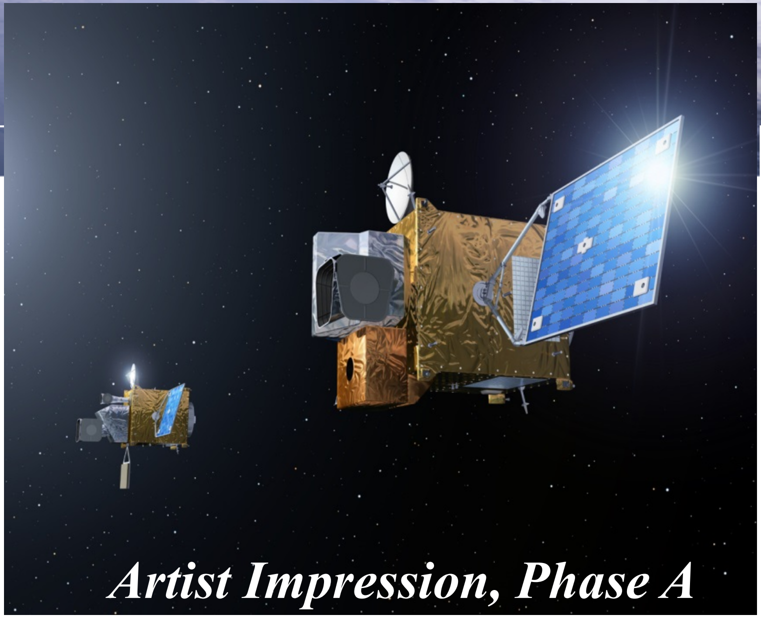
A new option for the US

GeoMetWatch™
ADVANCED, AFFORDABLE WEATHER.

- Privately owned commercial data provider ***leveraging GIFTS/HES technology development***
- Licensed for hyperspectral data collection under the Remote Sensing Act of 2003 (***NASA & NOAA cannot compete***)
- Will restore critical data for severe weather forecasting cancelled from GOES-R ***at a fraction of the cost, in record time!***
- ***This endeavor could become a really new way of doing business for environmental satellite data***

(Dave Crain, Q 15 Talk 12)

It is going to happen in Europe!



Artist Impression, Phase A

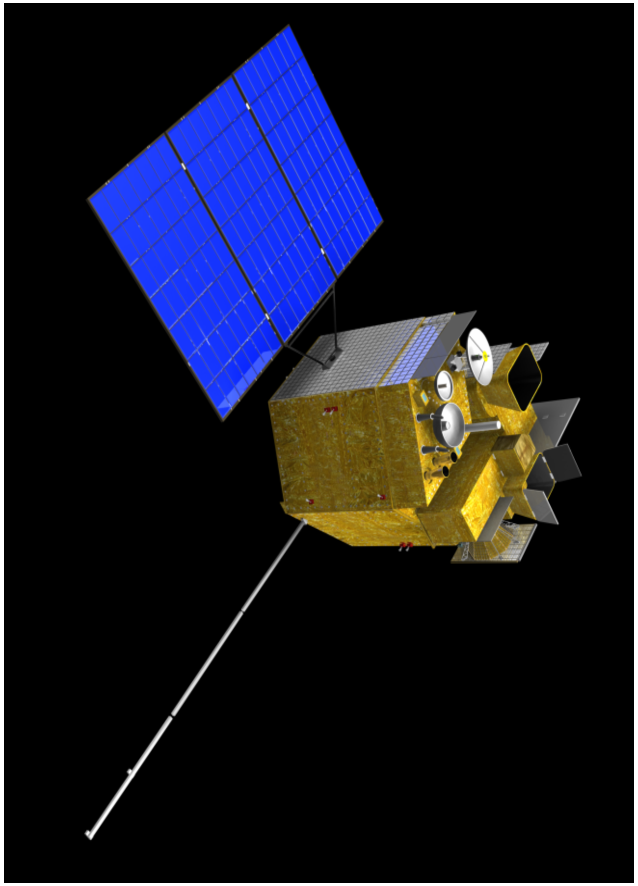
EUMETSAT/ESA plan for advanced IR Sounder (IRS) to fly on Meteosat 3rd Generation (MTG) in 2018

EUMETSAT

China has an Advanced Sounder Program too!

Next Generation of GEO satellite FY-4

4 main instruments



Prototype structure of FY-4A

Interferometric Infrared Sounder

Multiple Channel Scanning Imager

Lightning Mapper

Solar X-EUV imaging telescope
(not available on 1st satellite)

No.	Plan Launch	Design Life	Status
FY-4A	2014	5 years	R&D
FY-4B	2017	7 years	Op.
FY-4C	2019	7 years	Op.

Jun Yang, GOES Users Conference, 4 Nov 2009

C. Advanced GEO Wx Sounder & Trace Gas Imaging FTS Summary

Technology is not limiting US progress toward this extremely valuable asset

NOAA needs to prioritize meeting this need in the GOES-R time frame

D. IR Climate Benchmark (a la CLARREO)

A New Hyperspectral Climate Benchmark Mission is needed to provide:

- Unbiased spatial and temporal sampling
  - **90 degree, true polar orbit**
  - **Multiple, spaced orbits for seasonal coverage**
- Broad, contiguous spectral coverage, including Far IR
  - **High Information Content, not calorimetry**
  - **Intercalibration to tie POES and GEO to consistent standard**
- On-orbit Verification and Testing
  - **Unequivocal calibration to 0.1 K 3-sigma**

Earth Radiation Budget, *the old way*

13 Oct 1959-Feb 1960 Explorer 7

The 1st meteorological satellite instrument to observe the Earth

- Radiometer designed by Verner Suomi & Robert Parent
- Omni-directional spheres
- 3-color (black, white, gold)

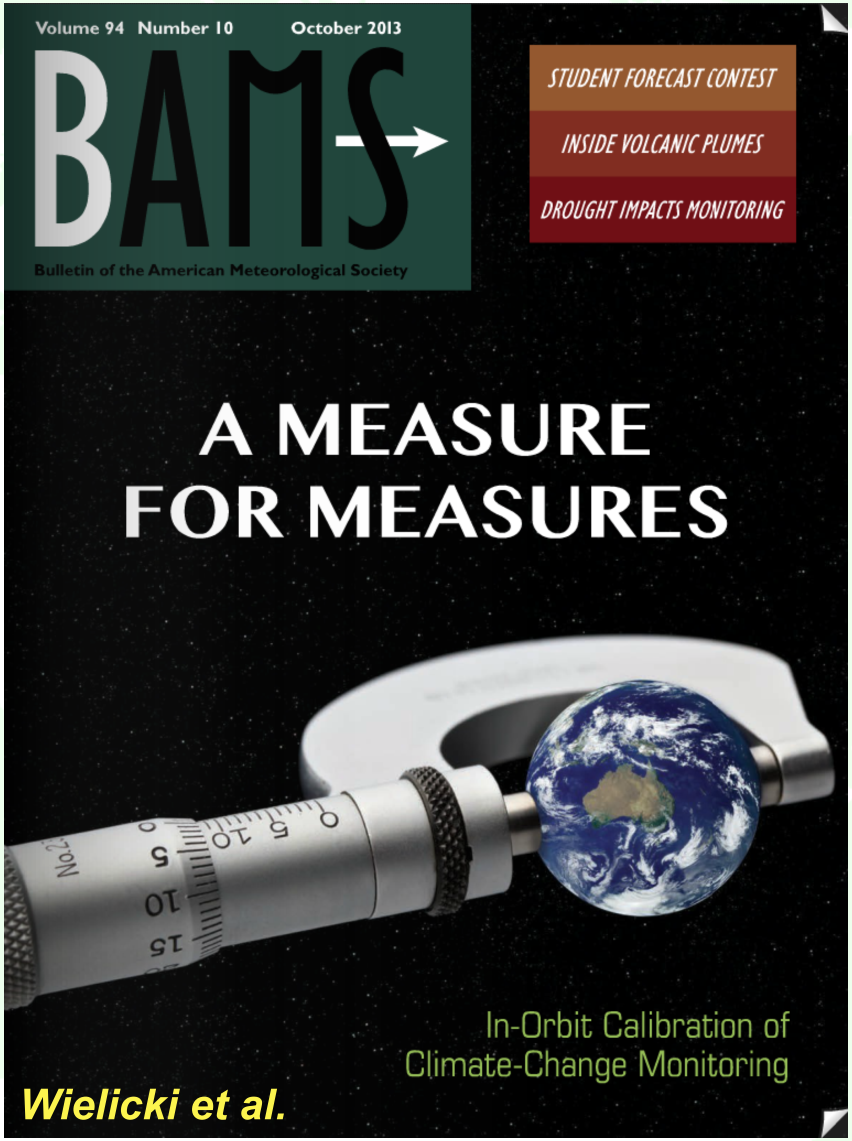
Spectrally integrated obs continue today

An outgrowth of measuring the energy budget of a corn field

NASA just in its 2nd year

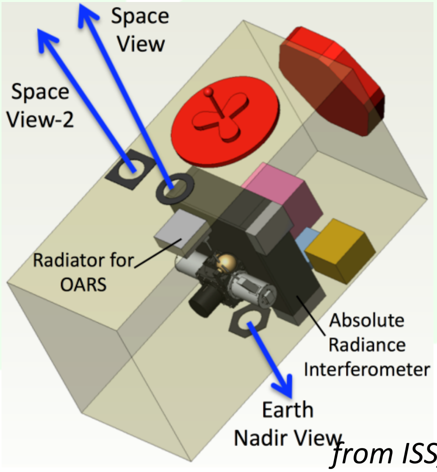
Introduction to CLARREO and ARI

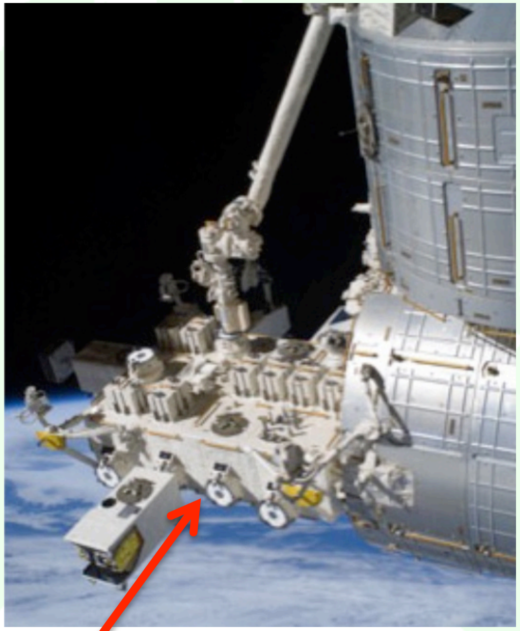
- **CLARREO** (Climate Absolute Radiance & Refractivity Observatory) a 2007 Decadal Survey Tier 1 mission
  - IR & Reflected Solar spectra coupled with GPS occultation data offer unprecedented accuracy to provide much higher climate change sensitivity than existing climate records (from total integrated IR & Solar data)
  - Metrology lab on-orbit serves as "NIST in orbit"
- **CLARREO** to Benchmark the Earth's climate
  - Analogous to marking a glacier's current extent
- **CLARREO** to be an Inter-calibration Standard
  - GSICS (Global Space-based Inter-Cal System)
  - e.g. Greatly enhancing the value of the climate record from high spectral resolution IR sounders starting in 2002 (AIRS, IASI, CrIS)
- **Absolute Radiance Interferometer (ARI)** is an IR prototype instrument with new on-orbit verification technology ready for CLARREO or a pathfinder mission



ARI for CLARREO Pathfinder Mission

- **Vacuum Testing of CLARREO Flight Prototype** ***Absolute Radiance Interferometer (ARI)*** **has demonstrated 0.1 K 3-sigma performance of the**
  (1) Calibrated FTS (CFTS) and
  (2) On-orbit Verification and Test System (OVTS),
  bringing the full ARI system to TRL 6
- **The next step should leverage NASA ESTO's investment with a spaceborne demonstration as a CLARREO IR pathfinder. Flight on the International Space Station (ISS) is being considered.**



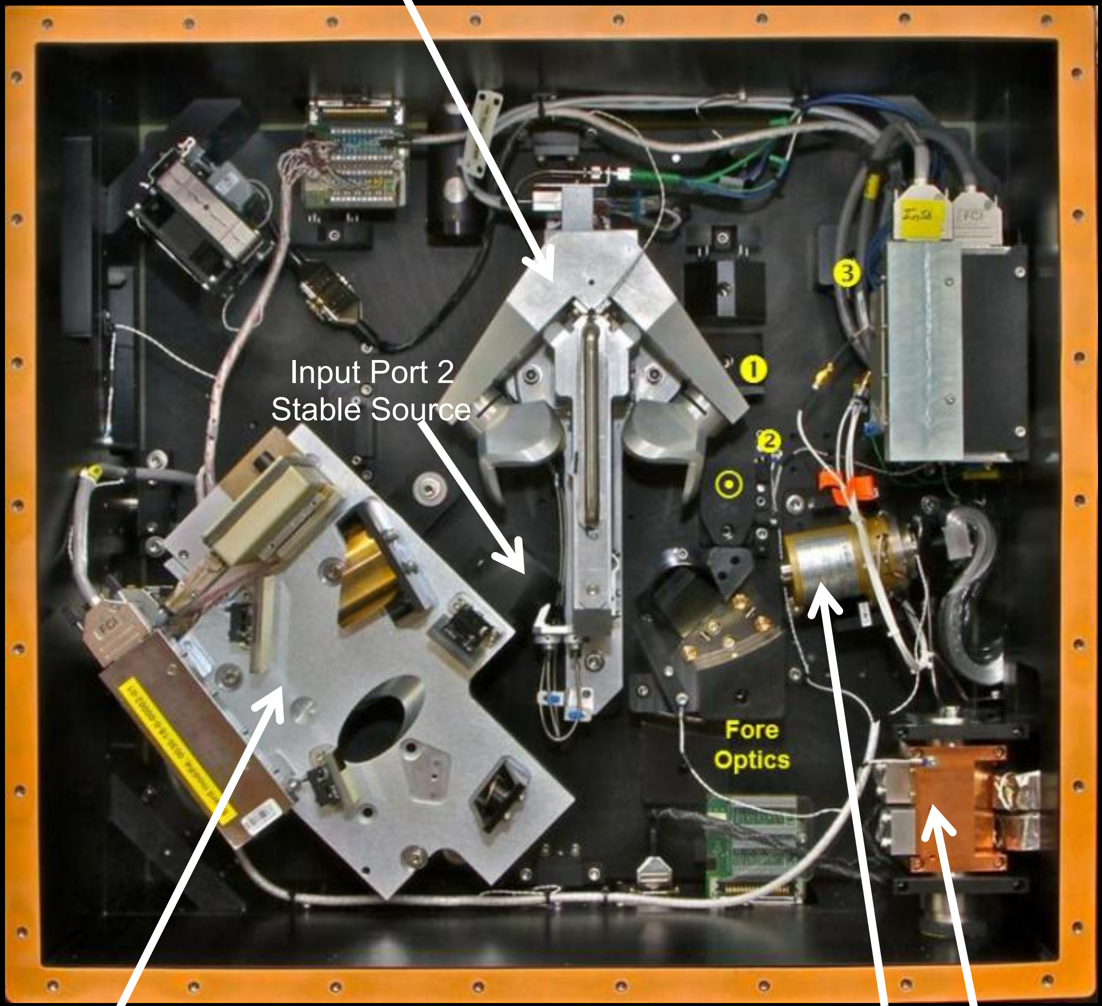


JEM-EF EFU Site #4
from ISS/DS/ESM Cross Mission Study

Absolute Radiance Interferometer (ARI) Prototype

with a short upgrade path to flight

ABB Bomem Interferometer Modulator "Wishbone"



Aft Optics 1/ Pyro-detector

Aft optics 2 (MCT/InSb) Sterling Cooler Compressor

Calibrated FTS

- Corner-cube interferometer used in 4-port to avoid double pass; Strong flight heritage
  - 0.5 cm^{-1} resolution (±1 cm OPD)
  - 1.55 μm diode laser for interferogram sample control & fringe counting
  - 10 cm CsI single-substrate beamsplitter
- Fore optics designed to
  - minimize polarization effects
  - minimize sizes of calibration/ verification BBs & reflectivity sources
  - minimize stray light by providing effective field and aperture stops
  - maximize energy throughput
- 3-50 μm Spectral Coverage
  - Highly linear pyroelectric detector, all reflective aft optics: 10-50 μm
  - Cryo-cooler for MCT & InSb semi-conductor detectors: 3-18 μm

Absolute Radiance Interferometer (ARI) Prototype

with a short upgrade path to flight

On-orbit Verification and Test System (OVTS) Technologies

❶ On-orbit Absolute Radiance Standard (OARS) cavity blackbody using three miniature phase change cells to establish the temperature scale from -40, to +30 C to better than 10 mK

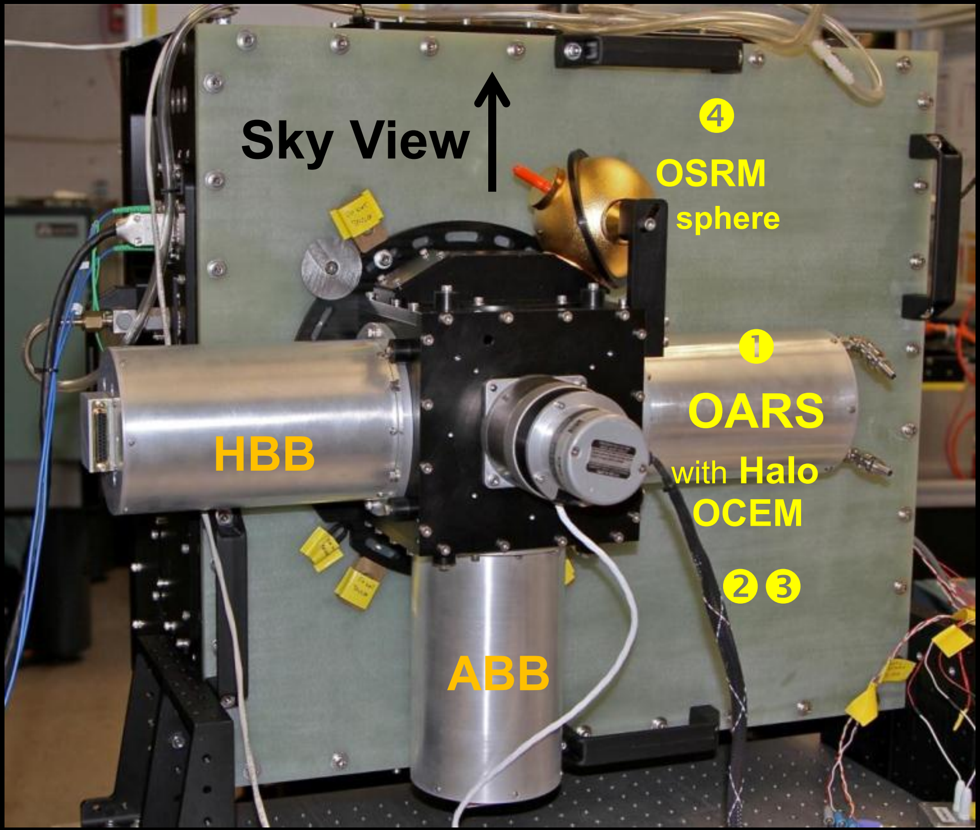
❷ On-orbit Cavity Emissivity Module (OCEM) using Heated Halo source allowing the FTS to measure the broadband spectral emissivity of the OARS to better than 0.001

❸ OCEM-QCL* using a Quantum Cascade Laser source to monitor changes in the mono-chromatic cavity emissivity of the OARS & Cal BB to better than 0.001

❹ On-orbit Spectral Response Module* (OSRM) QCL used to measure the FTS instrument line shape

***** QCL functions demonstrated separately***

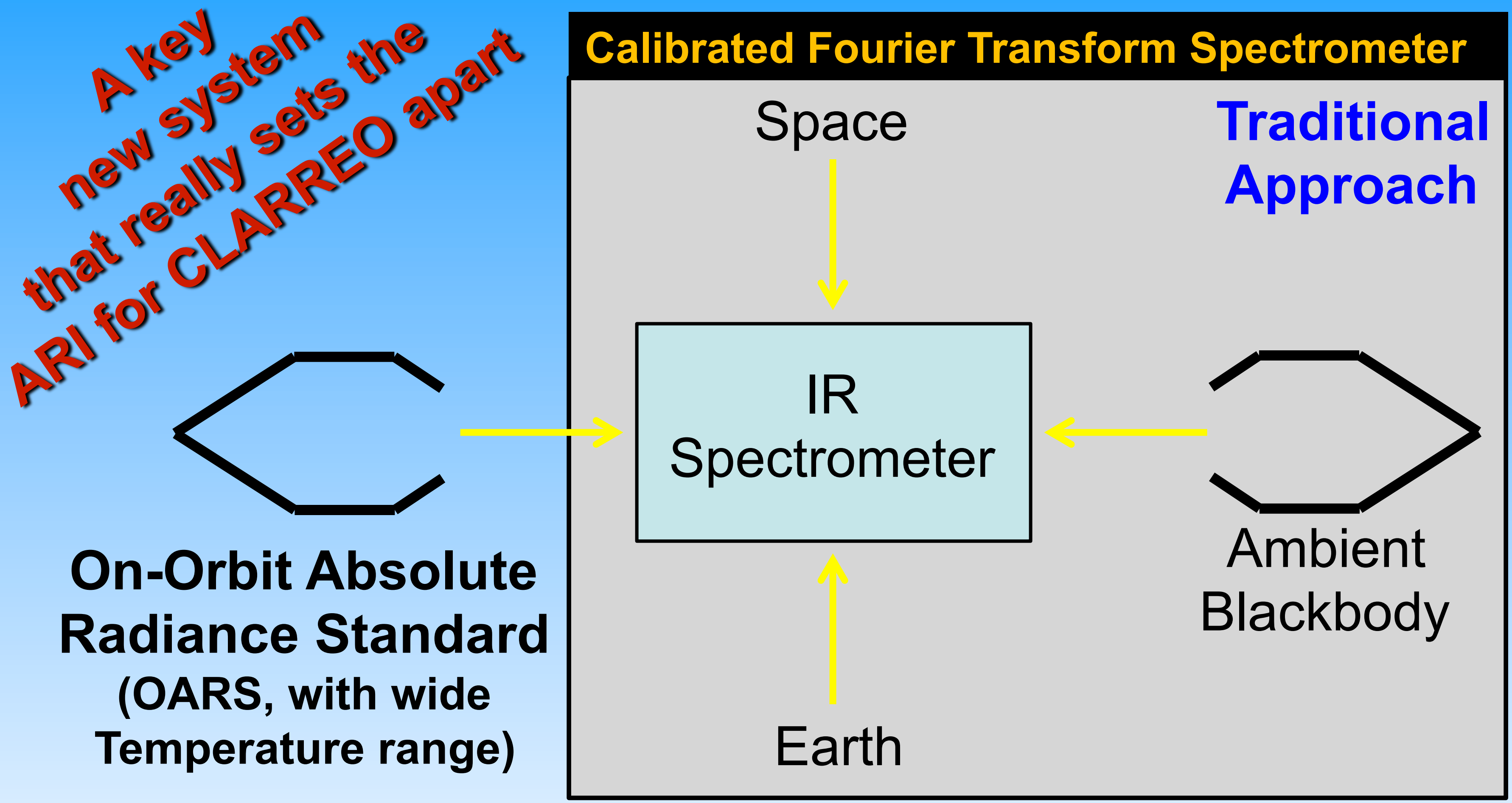
OVTS Sources



Calibrated FTS Blackbodies (HBB & ABB)

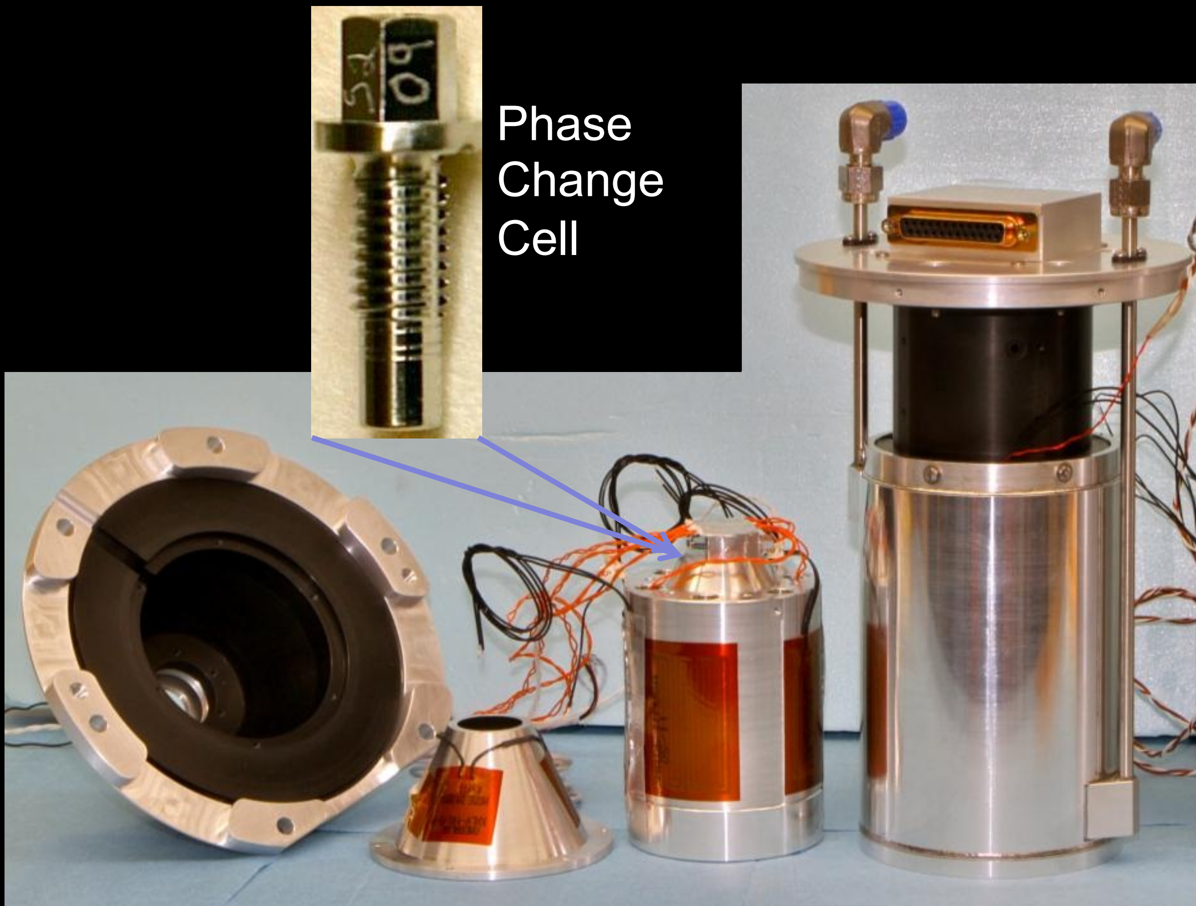
All components at flight scale

On-Orbit Verification and Test System



OVTS Provides On-Orbit, End-to-End Calibration Verification & Testing Traceable to Recognized SI Standards

On-orbit Absolute Radiance Standard OARS

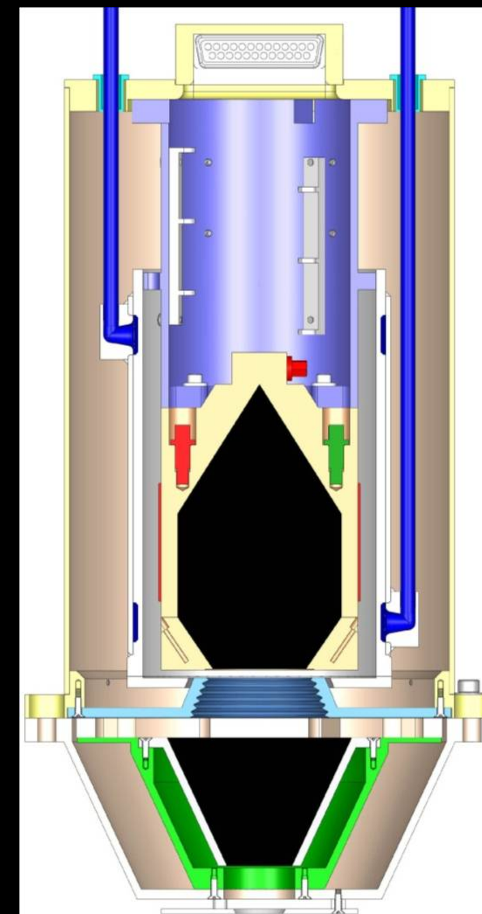


Heated Halo
& Halo Insulator

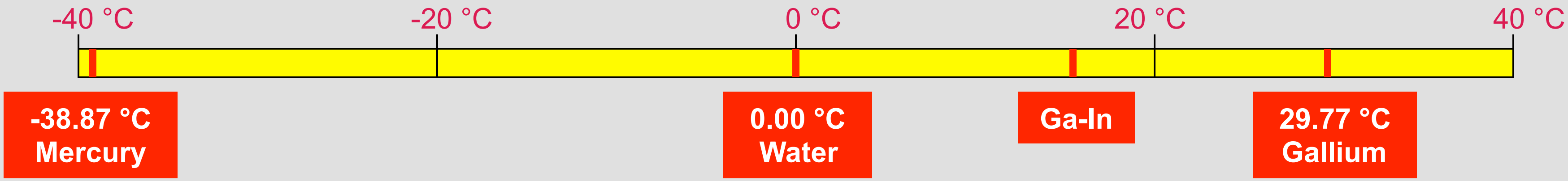
Cavity

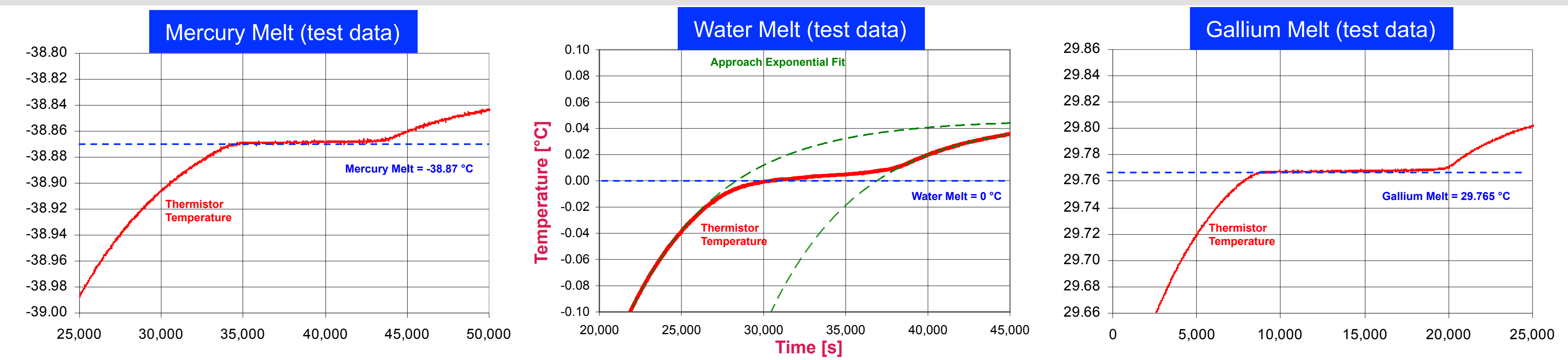
Inner Shield
& Isolator

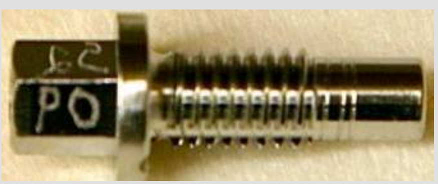
Assembly Diagram



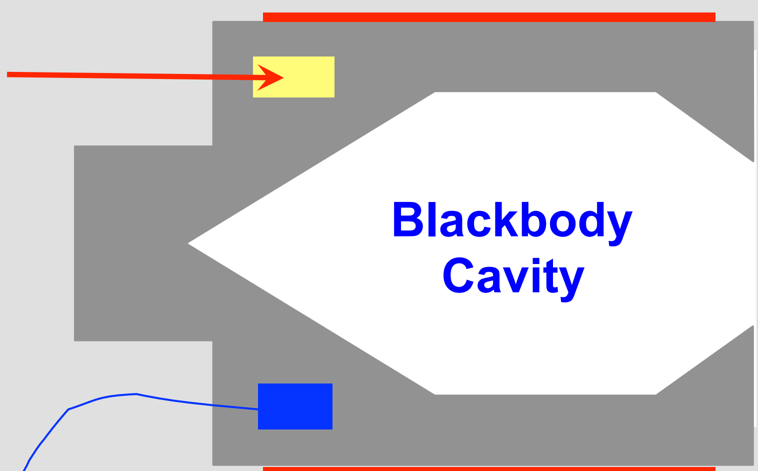
Temperature Scale Established to < 10 mK on-orbit







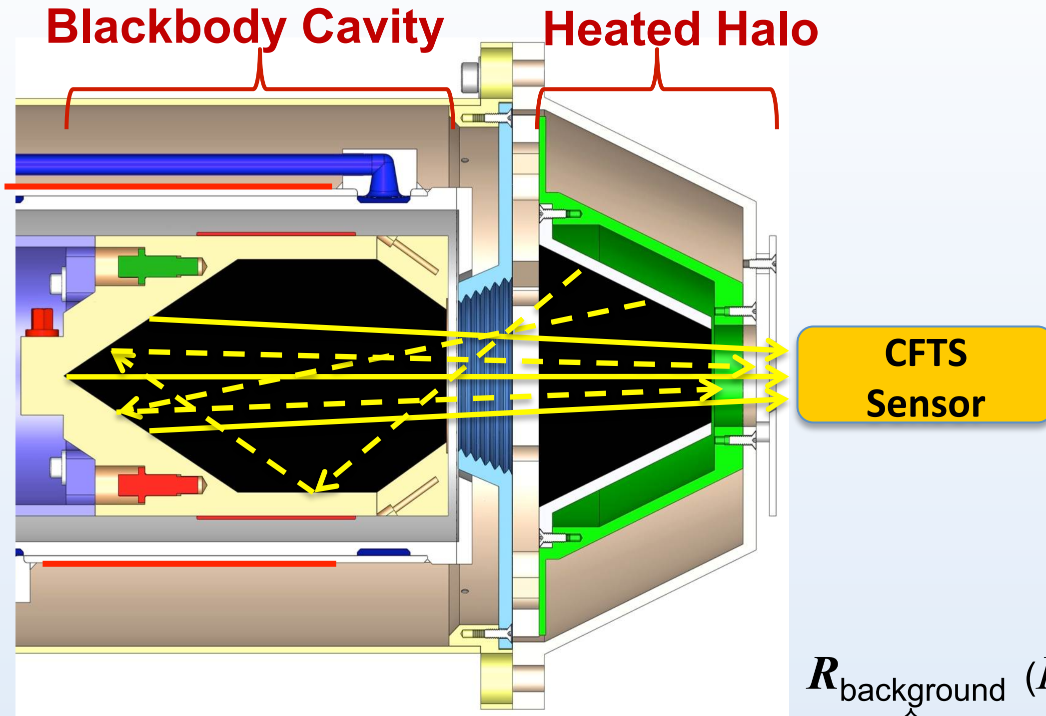
Phase Change Cell (Ga, H_2O, or Hg)



Thermistor (plotted above)

Plateaus (shown in plots) provide known temperatures to better than 5 mK

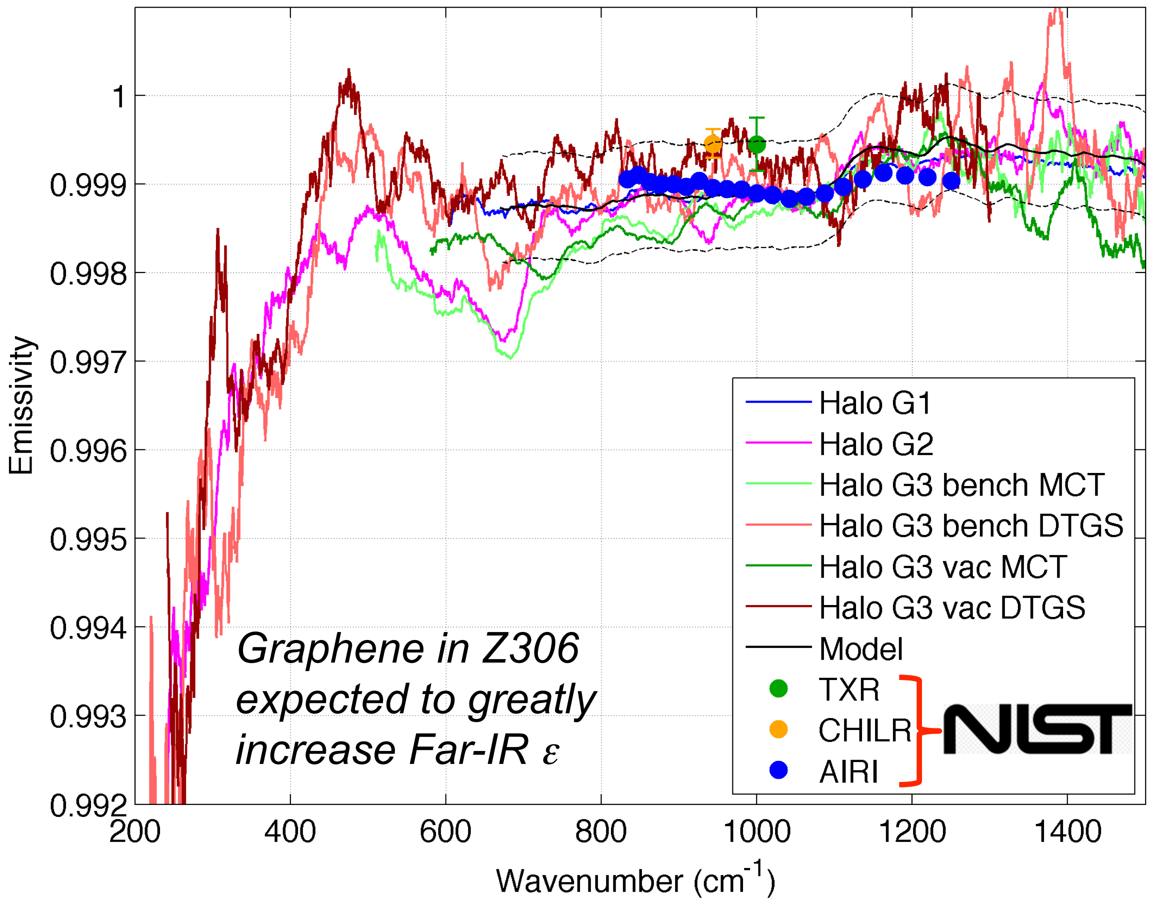
Heated Halo Concept



$$R_{\text{scene}} = \underbrace{\varepsilon \bullet B(T_{\text{BB}})}_{\textit{Radiance emitted from BB}} + \underbrace{(1-\varepsilon) \bullet \overbrace{[F \bullet B(T_{\text{Halo}}) + (1-F) \bullet B(T_{\text{room}})]}^{\boldsymbol{R}_{\text{background}}\ (F\text{=fractional view to Halo})}}_{\textit{Background Radiance Reflected from BB}}$$

$$\left\langle 1-\varepsilon_{\tilde{\nu}}(t) \right\rangle_t = \left\langle \frac{R_{\text{scene}}(t) - B[T_{\text{BB}}(t)]}{R_{\text{background}}(t) - B[T_{\text{BB}}(t)]} \right\rangle_t$$

Blackbody Emissivity Measured to < 0.001 on-orbit

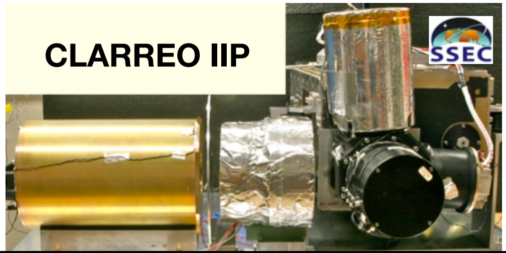


3-σ emissivity of 0.0006 uncertainty indicated by dashed lines applied to model

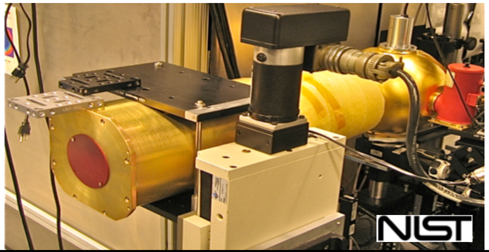
Good agreement with NIST measurements

Far IR tests with Graphene in Z306 are in progress

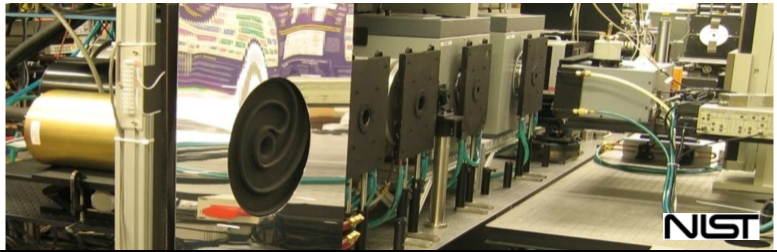
UW Heated Halo



NIST CHILR



NIST AIRI



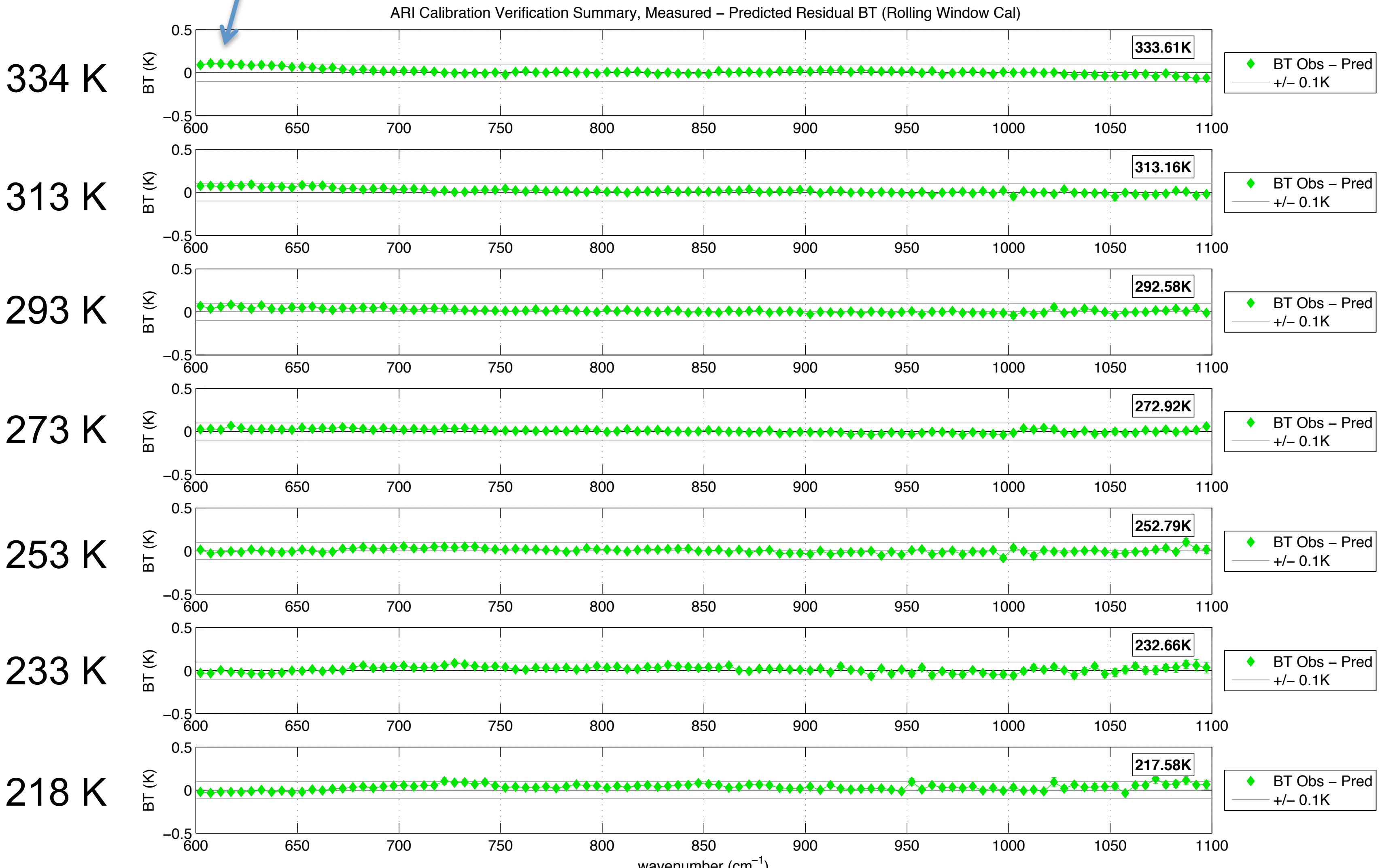
Brightness Temperature Accuracy Verified to < 0.1 K

(CFTS calibrated - OARS verification)

MCT

Correction of field stop problem removes this error

Error bars only include statistical error in measurement

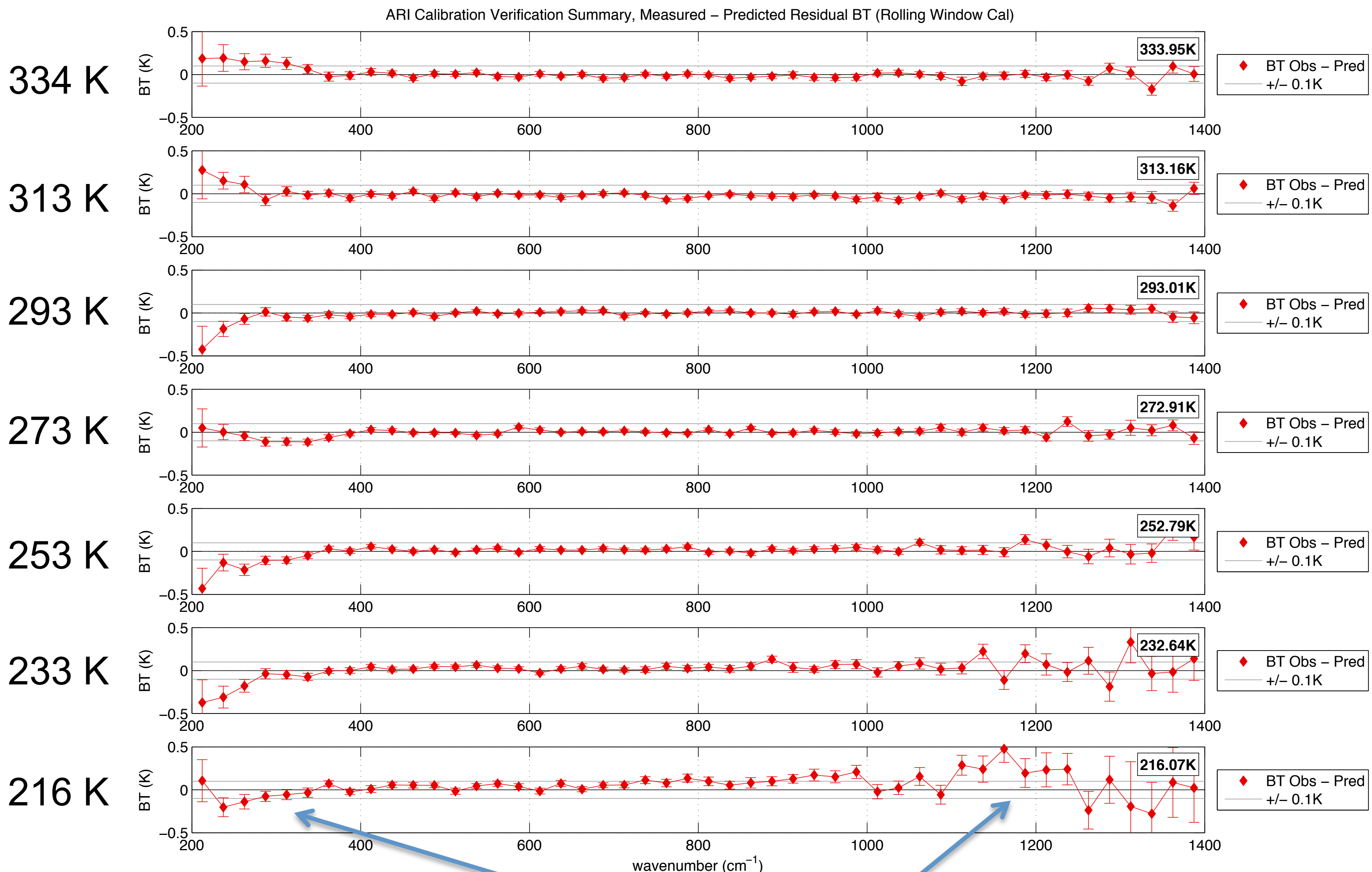


Spectral Averaging Bin Width is 5 cm^{-1}

Brightness Temperature Accuracy Verified to < 0.1 K
(CFTS calibrated - OARS verification)

DTGS

Error bars only include statistical error in measurement

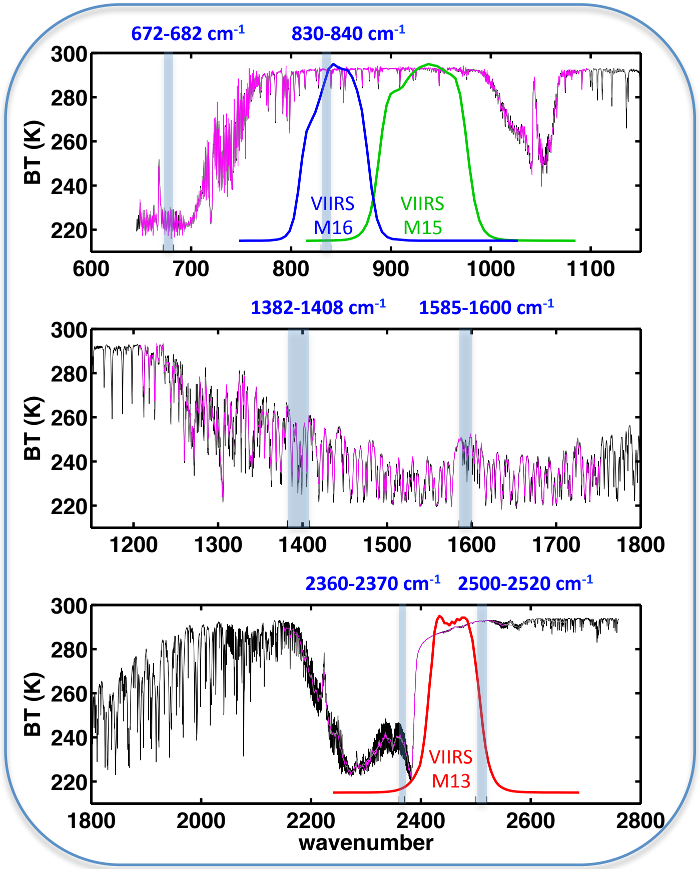


Spectral Averaging Bin Width is 25 cm^{-1}

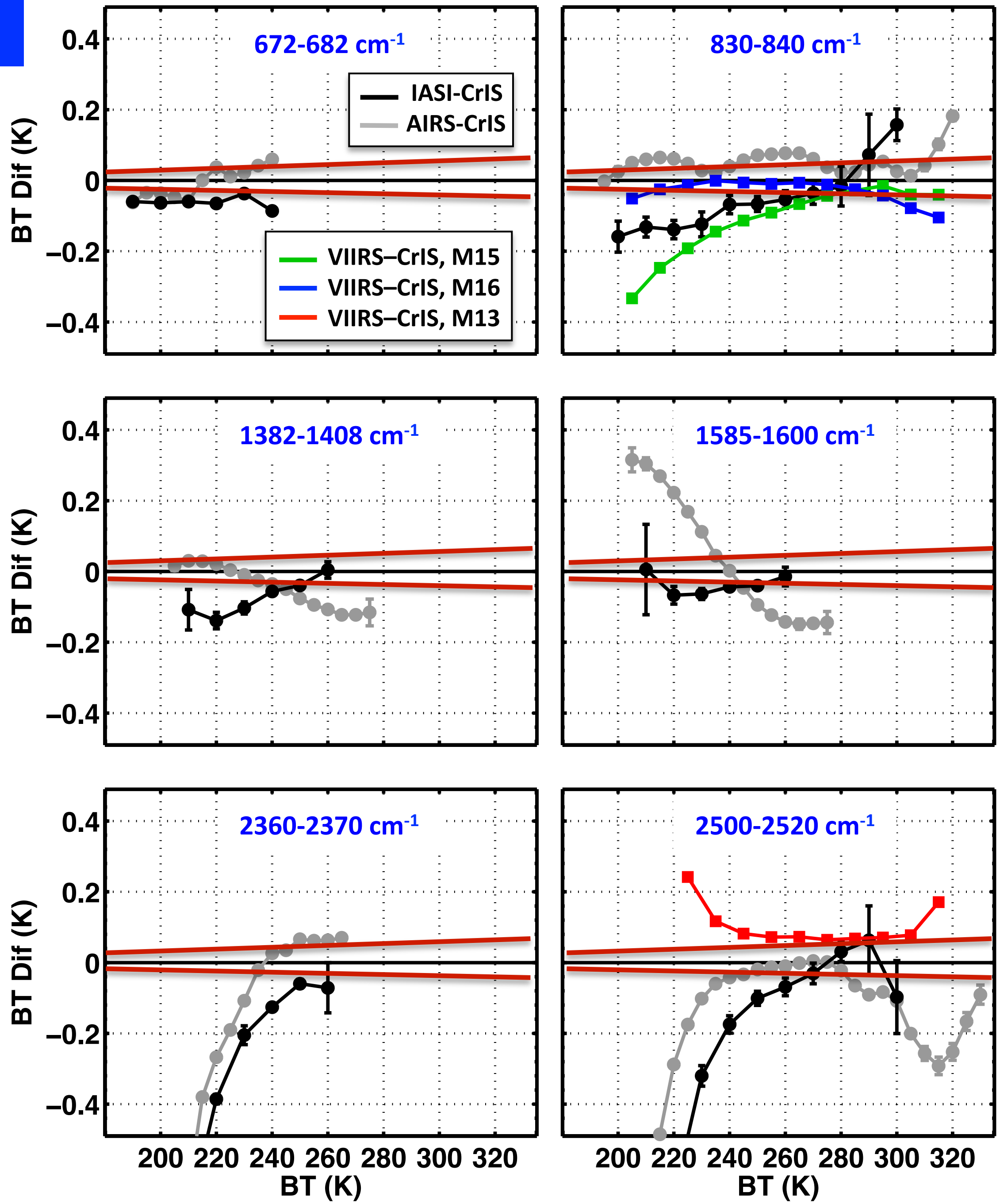
Bin averaged result subject to low SNR at band edges

Pathfinder Mission Offers Valuable On-orbit Standard

- ARI not-to-exceed Uncertainty provides better "truth"
- Residual from CrIS for:
  - AIRS
  - IASI
  - VIIRS: M13, M15, M16

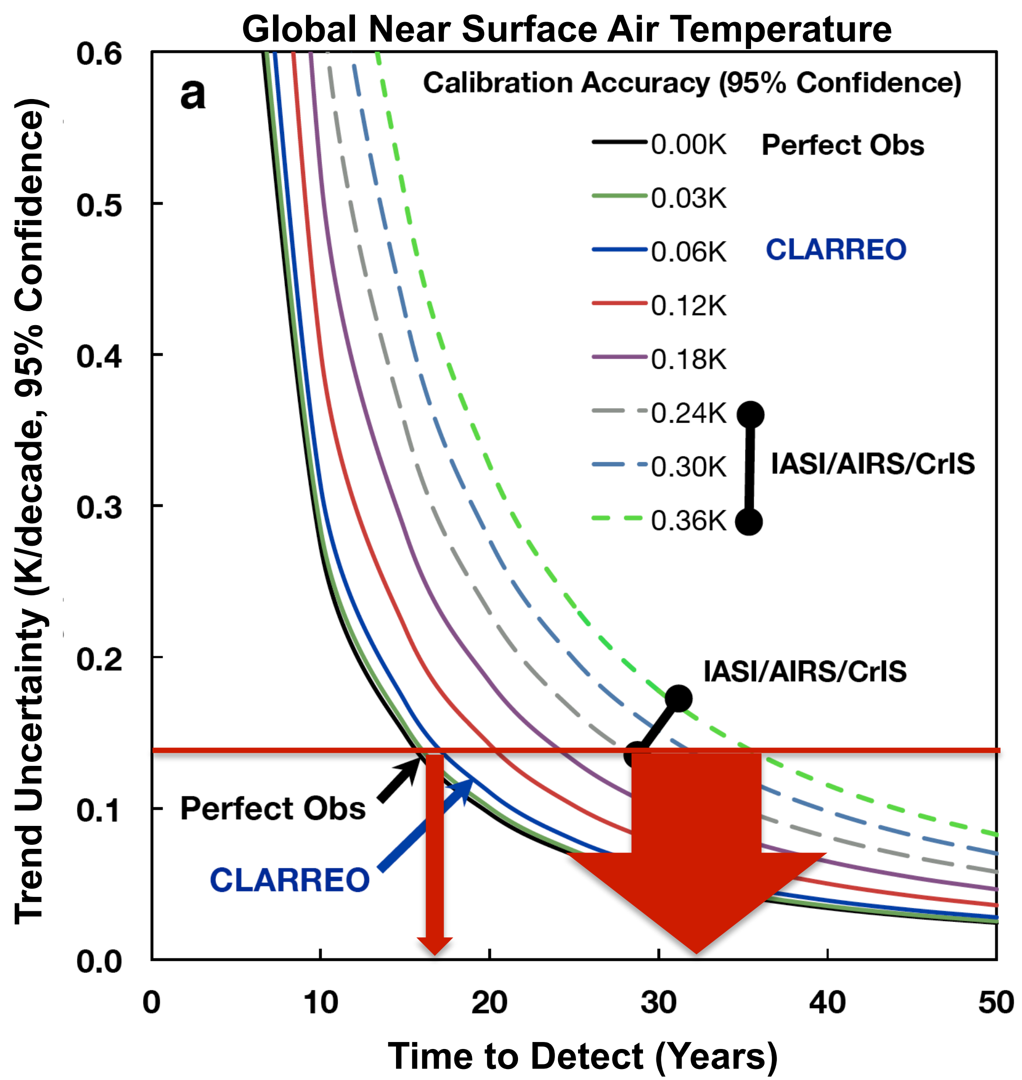


Summary of recent Inter-calibrations



ARI Accuracy Offers Substantially Reduced Time to Detect Global Climate Change

Achieving Climate Change Absolute Accuracy in Orbit,



Example with ~ factor of 2 shorter Time to Detect

Wielicki et al., BAMS, 2013

Summary of ARI Status

- **CLARREO:** Efforts of the NASA Science Definition Team have documented compelling science and societal benefits from Benchmarking the Climate State and Inter-calibrating other Satellite Sensors (Wielicki, et al., 2013)
- **CLARREO IR Flight Prototype, ARI:** Recent UW Vacuum Testing combined with prior UW/Harvard IIP technology developments and test results demonstrate capability to meet CLARREO mission performance requirements
- **ARI Technical Readiness:** NASA Earth Science Technology Office (ESTO) has assigned a Technical Readiness Level of 6 supporting readiness for a flight mission
- **International Space station:** ISS offers an attractive and economical avenue to a CLARREO pathfinder mission, especially given the recent ISS lifetime extension until 2024
- **CLARREO pathfinder on ISS:** Would provide economical risk reduction for the full CLARREO mission and a chance to improve the overall accuracy of operational environmental satellite capabilities and leverage them to start a global benchmark record

D. IR Climate Benchmark Summary (a la CLARREO)

Climate Benchmark Missions are now technologically viable and need to be included in operational requirements for the foreseeable future